Department of Applied Mechanics

Design method for safe ship structures

Alan Klanac

Aalto University

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Abstract

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Abstract

At present ships are designed to satisfy the minimum requirements for safety. And history shows that this practice does not suffice, and nor is it sustainable. A new paradigm is needed. This thesis aims to contribute in that respect by proposing a design method that should move ship safety beyond the minimum requirements as much as possible and as long as it is economically sound. The thesis focuses mostly on environmental safety in the event of accidents such as collisions and grounding. A special feature is the consideration of maritime stakeholder preferences regarding safety and profitability. This is an underlying element in all the analysis performed and conclusions reached.

This design method features new approaches in multi-objective optimization of ship structures and in advanced decision making for design selection. The multi-objective optimization is based on evolutionary algorithms, more precisely the genetic algorithm (GA) with advanced treatment of design constraints and objectives. Through the approach of vectorization, the GA becomes not only more efficient, but also more flexible in use, bearing in mind the complexity and demands of accident analysis for optimization. The decision making is established on the concepts of Game Theory, resulting in a new criterion for design selection, the Competitive Optimum, based on the maximal concurrent satisfaction of stakeholder preferences.

The proposed design method is intended in particular for ship structural design projects, permitting the definition of hull structural scantlings, or even hull topology if desired. The approaches to multi-objective optimization and design selection that are introduced possess a wider basis of application, and are extensible to other fields in maritime safety and naval architecture.

The results of the thesis provide several relevant conclusions with an impact on practical naval architecture. For example, i) by increasing ship crashworthiness, significant risk reduction can be attained, ii) raising safety is economically justified if the benefits to the public are considered alongside those of the industry, and iii) the crashworthiness of ships can be controlled effectively with conventional double-bottom and double-sided structures.

Keywords Safety, structure, design, decision-making, optimization, Game Theory, Nash Equilibrium, tanker, Ro-Pax

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Preface

After a long journey I am happy to write this preface to a thesis that I conducted in an adventure that involved moving and living in Finland for six years, moving back to my homeland of Croatia, living through my wife's successful dissertation, and, most beautiful of all – getting a daughter!

In this time I was financially supported first of all by the *Helsinki University of Technology (TKK)*, now *Aalto University*, then by the *European Commission* and *TEKES* through many of the research projects I took part in (SANDWICH, TÖRMÄKE, SAND.CORe, MARSTRUCT, CONSTRUCT, IMPROVE), and by the *Merenkulunsäätiö* foundation, which financed my travels to conferences and a summer school. In the final stages of writing this manuscript, I was supported by the works of my undertaking, *as2con-alveus ltd.* The support of these organisations is hereby kindly acknowledged and deeply appreciated.

Finances are important, but a personal touch is much more so. Therefore there would be nothing of this thesis if it had not been for three people. The first was my supervisor, Prof. Petri Varsta. He helped and pushed me in every step of this journey and was a constant presence, encouraging and criticising when it was needed and when it was necessary. This I will never forget. He was like a father to me.

The second person was Prof. Pentti Kujala. He was the reason that I moved to Finland, he motivated my first research steps, and he instructed me how to write my first papers. And he became a friend.

The third person that made this thesis possible was my spouse, Natasa Golik Klanac. She was a pillar that supported me overzealously not only personally, but scientifically as well. I loved our late-night discussions about value, utility, stakeholders, the Internet, safety, websites, ships, lifts, etc. I would never have been able to do it if I had not had her.

Besides these three people, there were others that helped, pushed, and motivated. First of all, I wish to express my gratitude to my friends and colleagues at *TKK*, especially to Sören Ehlers and Jani Romanoff, who selflessly assisted in the final preparations of this manuscript. Besides them, I thank my article co-authors, Risto Jalonen and Jasmin Jelovica, as well as the rest of the research crew, Tommi Mikkola, Hendrik Naar, Heikki Remes, and Kristjan Tabri.

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I also wish to thank Prof. Kalyanmoy Deb, Prof. Kaisa Miettinen, and Petri Eskelinen for reading my unfinished paper manuscripts and sharing their experience.

Big thanks go to my 'new' friends and colleagues at *as2con-alveus ltd*: Darko Frank, Petar Nikolic, Drazen Polic, Nikola Buneta, Teuta Duletic, Mamadou Basic, Maja Kovac, Ksenija Cukovic, Sandro Erceg, Ljiljana Sincic Buneta, Boris Erceg, Nikolina Rebic, Dean Selihar, Primorka Dzeko, Masa Paliska, Dario Buterin, Tomislav Tomac, Anita Buterin, Marko Simic, Igor Marijanovic, Tea Arrigoni, Dean Prelec, Hrvoje Paskvan and Davor Bolf.

I thank my friends from life: Melita & Ivica, Dea & Sasa, Gabi & Igor, Kristina & Kreso, Ana & Dusko, Irena & Vlado, and Tanja & Paul.

I thank my wider family for all their support. I thank my mother for her love and for patiently waiting for 'her turn'. In the end, I thank especially my daughter Anneli for being the loveliest creature on the planet.

Rijeka, December 2010

Contents

Papers

[P1] Klanac A, Jalonen R, Varsta P. Multi-stakeholder decision-making in the risk-based design of a RO-PAX double bottom for grounding. *J Eng Maritime Environment*, **221**:1, 2007, 1-15.

[P2] Klanac A, Jelovica J. Vectorization and constraint grouping to enhance optimization of marine structures. *Marine Structures*, **22**:2, 2009, 225-245.

[P3] Klanac A, Ehlers S, Jelovica J. Optimization of crashworthy marine structures. *Marine Structures*, **22**:4, 2009, 670-690.

[P4] Klanac A, Varsta P. Design of marine structures with improved safety for environment. *Reliability Eng System Safety*, 96:1, 2011, 75-90.

List of symbols

<u>Alphabetic symbols</u>

a	weight for attribute importance
d	depth of penetration, distance, weighted Euclidean distance
E	Young's modulus, energy, risk of environmental damage
f	objective function
F_p^q	aggregated objective function
g	constraint function
gen	generation
G, H	mathematical games
I	reference point
k	scaling constant nullifying the effects of differing nature between attributes
l	line passing through the ideal vector 1 and the arbitrary weighting vector ω
L	risk of loss of life
m	mass
M	risk of material damage
O	costs for the ship owner/operational loss
p	probability
P	costs for the shipyard/penalty function
P	set of all permutations
q	transformed constraint
r	value of any attribute under uncertainty/
R	risk in general
s	set of all strategies available to stakeholder
$\hat{\mathbf{S}}$	rational reaction set
u	payoff to stakeholder/utility function
$\hat{\boldsymbol{u}}$	centre of minimal isometric cone
$\breve{\boldsymbol{u}},\breve{\boldsymbol{v}}$	ideal vector

$\underset{\smile}{\boldsymbol{u}},\underset{\smile}{\boldsymbol{v}}$	nadir vector
$\tilde{\boldsymbol{u}}$	Nash Equilibrium
$\boldsymbol{u}^{\bullet}$	product stakeholder utility function
$\boldsymbol{u}^{*},\boldsymbol{v}^{*}$	Competitive Optimum
u^{+}	additive stakeholder utility function
$\mathbf{U}$	set of all feasible design alternatives
$\hat{\mathbf{U}}$	set of Pareto optimal design alternatives
$\mathbf{V}$	non-normalized set of all feasible design alternatives
w	weighting coefficient
x	design variable
$\boldsymbol{x}$	Pareto optimal design alternative
$\boldsymbol{x}^{**}$	scalar optimum
$\mathbf{X}$	design space
$\hat{\mathbf{X}}$	Pareto frontier set
y	objective/attribute value
$\mathbf{Y}$	objective/attribute space
$\hat{\mathbf{Y}}$	Pareto frontier set
$\boldsymbol{z}$	hypothetical design alternative in the utility space
$\mathbf{Z}$	utility space

Greek symbols

α	normalisation function
γ	inverse normalisation function
ε	strain
η	strain hardening index
λ	Chebyshev metrics in normalised utility space
Λ	minimal isometric cone of Chebyshev metrics
υ	Poisson coefficient
φ	fitness function
ω	weight for stakeholder importance
$\boldsymbol{\Omega}$	feasible set
$\hat{\boldsymbol{\Omega}}$	set of feasible Pareto optima

List of abbreviations

CLC	Civil Liability Convention
EMSA	European Maritime Safety Agency
GA	Genetic Algorithms
IMO	International Maritime Organisation
ISM	Institute for Supply Management
MARPOL	International Convention for the Prevention of Marine Pollution from Ships
MaSSCoR	Maximum Stakeholder Satisfaction in Competitive Relationships
NE	Nash Equilibrium
OPA	Oil Pollution Act
SOLAS	Safety of Life at Sea

List of publications and author contributions

This thesis consists of an introductory summary and the following four papers:

[P1] Klanac A, Jalonen R, Varsta P. Multi-stakeholder decision-making in the risk-based design of a RO-PAX double bottom for grounding. *J Eng Maritime Environment*, **221**:1, 2007, 1-15.

Klanac established the concepts of the multi-stakeholder decision-making methodology, devised the decision criterion of the Competitive Optimum, performed the decision modelling and analysis, established the final conclusions, and wrote the paper. Jalonen established the quasi-static grounding model and performed the risk analysis, while Varsta assisted with valuable comments.

[P2] Klanac A, Jelovica J. Vectorization and constraint grouping to enhance optimization of marine structures. *Marine Structures*, **22**:2, 2009, 225-245.

Klanac established the method of vectorization and constraint grouping, wrote the pseudo-code of the genetic algorithm, conducted the optimization test calculations, established the conclusions, and wrote the paper. Jelovica assisted in performing the optimization test runs, contributed with valuable comments, and assisted in the writing of the paper.

[P3] Klanac A, Ehlers S, Jelovica J. Optimization of crashworthy marine structures. *Marine Structures*, **22**:4, 2009, 670-690.

Klanac established the 'two-phase' multi-objective optimization procedure, conducted the optimization, reached the general conclusions, and wrote the paper. Ehlers established a rapid numerical procedure for the evaluation of crashworthiness, while Jelovica assisted in conducting the optimization and writing.

[P4] Klanac A, Varsta P. Design of marine structures with improved safety for environment. *Reliability Eng System Safety*, 96:1, 2011, 75-90.

Klanac extended the methodology of the multi-stakeholder decision making, e.g. the validity of the Competitive Optimum solution for a problem involving any number of stakeholders, then applied the extended methodology to provide an answer to the question of the optimal amount of investments into safety required. Klanac also performed the calculations on the illustrative example demonstrating the overall methodology, and wrote the paper. Varsta contributed with valuable comments.

Original features

How much should be invested into safety, or how much safety is enough? These questions have been tormenting seamen, engineers, and businessmen for as long as cargo and people have been transported over the sea. To sustain trust, society in a wider sense set minimum safety requirements, balancing between the protection of life, cargo, and the environment and the business aspect. However, every new major accident caused the very same requirements to be raised, indicating that they clearly lagged behind the true demands for safety. Instead of continuing along this path and analysing future risks in order to further improve the quality of minimal safety requirements, this thesis follows an alternative approach. It aims to provide a design methodology for the design of safe ship structures through which safety would be raised as much as is economically sound, with regard to both the short- and long-term impact on life, the environment, and business.

The following features of this thesis are believed to be original:

1. A condition of MaSSCoR – *maximum stakeholder satisfaction in competitive relationships* to allow for a balanced distribution of costs and benefits related to design with added safety [P1] & [P4];
2. The *Competitive Optimum* – a solution concept for multi-stakeholder decision-making problems in engineering [P1] & [P4];
3. Converting constraints into additional objectives for the problem of the structural optimization of the ship, or *vectorization* [P2];
4. The application of an absolute function to the constraint conversion [P2];
5. Partial constraint grouping [P2];
6. A two-step procedure for optimization, permitting the use of time-expensive response simulations of ship-to-ship collisions [P3];
7. Multi-objective optimization of tanker structures to maximise crashworthiness and minimise weight [P3], and

8. The selection of the optimal safe structure for a crashworthy tanker to maximise the concurrent satisfaction of stakeholder preferences [P4].

1. Introduction

1.1. Motivation and objectives

In this day and age the preservation of natural resources and sustainable development are of the utmost importance to society. Maritime transport plays a major role in this agenda. It is the most efficient mode of transport and thus a critical element of the world's sustainability.

Ships, as the fundamental means of maritime transport, carry cargo and serve both a commercial and a societal function. As a part of the global system, ships 'feed' their stakeholders: the yards that produce and maintain them, the owners that order and operate them, the charterers that use them to move goods, and the public that enjoys their continuous support of the supply chain.

In the long term ships are not only profitable, but they enhance profit-making. Yet they emit greenhouse gases, harm the environment with alien microorganisms through the ballast water, and have the capacity to abruptly change the environment through some catastrophic accident. Thus the public today are less and less tolerant towards the transportation of pollutant cargo, such as crude oil and its products, even though it is essential to their way of life.

One of the key elements in the management of these risks and benefits is ship design, including the design of ship structures. The design of ship structures is performed with the aim of the vessel satisfying commercial requirements, abiding by the IMO and Flag State regulations, and following the industry rules set by the Class societies. These rules and regulations determine the minimum safety requirements, and combining them with profitability presents a challenging task.

The ISO standard (2009) defines risk as the effect of uncertainty on objectives. Risk is typically quantified as a product of the casualty damage caused by an adverse event, and the probability of its occurring

Table 1. Historical perspective on the improvements in the minimum requirements of safety

Incident	Type of Accident	Convention instated/ updated	Measures instigated
Titanic (1912)	Collision with iceberg and loss of 1517 lives as a result of poor organisation of disembarkation and lack of lifeboats.	SOLAS (1914)	Watertight subdivision
Torrey Canyon (1967)	Grounding and spillage of 120,000t of crude	CLC (1969) MARPOL (1973)	Compulsory liability for damage imposed on the owner/Segregated ballast tanks for all new tankers w/t 70,000+ DWT
Amoco Cadiz (1978)	Grounding and spillage of 250,000t with claims of $2bn. presented by the French government	MARPOL (1978)	Segregated ballast tanks for all new tankers w/t 20,000+ DWT with protective arrangement
Herald of Free Enterprise (1987)	Flooding and capsizing with the loss of 193 lives	ISM / SOLAS Ch. II-1 (1990)	Operational safety management/Watertight subdivision of garage decks
Exxon Valdez (1989)	Grounding and spillage of 40,000t with damage of $3bn.	OPA (1990)/ MARPOL (1992)	All ships entering US waters to have double hulls/Double hull or risk-equivalent alternative arrangement for all newly-built ships
Scandinavian Star (1990)	Fire with the loss of 158 lives	SOLAS Ch. II-2	Requirements for fire zone subdivision
Bulk carrier lost in the early '90s.	Flooding and breaking	SOLAS Ch. XII (1997)	Bulk carriers to have sufficient strength to undergo partial flooding of compartments
Estonia (1994)	Flooding and capsizing with the loss of 852 lives	SOLAS Ch. II-1 (1995)	Requirements for flooding tolerance, instigated in SOLAS (1990), to be applied to existing ships and also newly-built ships
Erika (1999)	Breaking of hull and spillage of 20,000t with some €840 mil. worth of damage	EU EMSA (2002)	Accelerated phase-out of single-hull tankers
Prestige (2002)	Breaking of hull and spillage of approximately 60,000t of crude with total damage claimed of more than $2.5bn	Resolution on places of refuge (2003)	Ship in distress should be accepted to a harbour providing a controlled environment

(Slovic 1987). Safety, on the other hand, represents a condition of being protected from an adverse event (Oxford 2005). Safety is thus not quantifiable, but it can be ranked – with risk.

For ships, adverse events lead to problems such as loss of life, injury, and material and environmental damage. Thus their risks are regularly computed in order to check whether they are tolerable and determine whether the ship is safe from any accident. Minimum safety requirements in that case set the criteria that assure that the tolerable level of risk is not surpassed. Profit, as a measure of commerciality, especially short-term profit, is directly opposed to this definition of safety. For this reason, ships are designed to meet the minimum safety requirements.

There are two aspects of such a design approach that make it unsustainable. The first is the increased sensitivity to accident events as a result of the minimised safety margin. The tolerable levels of risk that determine the minimum safety requirements are often established empirically on the basis of historical observations. Thus, the minimum safety requirements are predominantly prescriptive, and they are by default limited by the present state of the art in technology and knowledge. The proof of this lack of sustainability can be found throughout maritime history. Every new major accident causes the minimum requirements to be raised in order to avoid similar events in the future. Remember the 'Torrey Canyon' accident that led to the CLC and, eventually, the MARPOL conventions (IPIECA/ITOPF 2007), and the incident of the 'Exxon Valdez', which, some 20 years later, caused the very same MARPOL to be updated, and also led to the OPA in the USA. See Table 1 below for a historical overview of improvements in the minimum safety requirements related to the design of ship structures.

The second aspect of a lack of sustainability is more profound. The distributions of the risks and benefits of maritime transport are not balanced between the maritime stakeholders. While those involved in the industry share the direct benefits of the trade, the public mostly fears the risks of accidents. The evidence for this can be found e.g. from the limits of liability to the damage caused by an accident defined by the CLC'92 (IPIECA/ITOPF 2007). Besides the potentially enormous damage to the public, this often causes disruptions to further developments of maritime transport. The public outcry regularly becomes irrational and is sometimes driven strictly by emotions, which in the end also influences strategic decision making[1]. Thus, ships should contribute to the sustainable

[1]Not world-famous, but a perfect example of the above argument is the case of the Croatian government project *Druzba Adria (2002-2005)*, through which Russian crude oil would had been exported by tankers from the North Adriatic, where it

development of maritime transport by providing either more benefits, i.e. being more efficient in trade, or being safer with regard to the preferences of all maritime stakeholders.

Since no similar method is known by the author to exist, the objective of this thesis is to provide a design method for safe ship structures that bridges the aspects of the lack of sustainability of the present design approach. The method should therefore help to define safer and more cost-effective designs with a better balance between the risks and benefits facing the stakeholders in maritime transport. To define the method, the following elementary research question is to be investigated:

'How can a safe ship structure be optimally designed for the varying preferences of multiple stakeholders when the distribution of risks and benefits amongst them is unbalanced?'

The method focuses on safe ship structures and their safety in accidental events, more precisely adverse collision and grounding events. It is based on the following research fields: i) maritime safety; ii) Game Theory; iii) ship structural optimization for multiple objectives, and iv) collisions and grounding of ships. The following state of the art outlines their research gap relevant to the objective of this thesis.

1.2. State of the Art

1.2.1. Maritime safety

As indicated by the IMO (2002) and the research community (Cho et al. 2006, Moore et al. 2009), to correctly undertake the establishment of maritime safety criteria, it is necessary to consider the maritime stakeholders and their preferences. Freeman (1984) describes stakeholders as actors whose interests in a system need to be addressed, while Roy (1996) notes that stakeholders demonstrate preferences towards options

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would arrive by a pipeline. The project, after many years of planning, infamously failed as a result of the intensive public outcry for the protection of the environment. Counter-initiatives were strictly conducted in Croatia, and nothing similar occurred in any other country with a shoreline touching the Adriatic. On the other hand, no specific measures were taken by the government or industrial stakeholders to implement safer operations beyond the minimum requirements of industry standards and international conventions. The irony of such an outcome is in the fact that during the time of the planning of the project, and still today, a very intensive import traffic of Arabian oil was conducted at the harbour of Trieste, Italy, also located in the North Adriatic. And no protests were heard. We can only wonder whether the outcome would have been different if the government and industry had had the capacity and willingness to implement e.g. ships with improved crashworthiness.

related to a system. In that sense, we can also observe the maritime stakeholders and their preferences regarding safety. All maritime stakeholders consider safety extensively in their activities, but they obviously do not possess the same preferences concerning it, e.g. how much is to be invested into averting a life lost or a ton of oil spilled.

Not everybody benefits from safety equally, and nor does everybody have a chance to manage safety in the maritime industry. For example, ship owners manage safety directly through operations, while the yard has the responsibility to meet the minimum requirements in designing and building a 'safe' product. The minimum requirements are elicited, on the other hand, through a stakeholder dialogue, which includes the industry and the regulators with the mandate of serving society overall. Because of their roles in society, the risks and profits they face differ significantly, and so do their preferences. This inevitably leads to a different ranking of priorities.

Bennett (2001) and Pöyhönen (2000) describe typical examples of these preferences. Their findings could be summed up as follows. The commercial aspects are primarily considered relevant by the industry, while society and individual professionals like seamen are more interested in improving safety but without any great willingness to bear the economic burden.

A number of studies seek to establish criteria that follow these findings (Vatn 1998, Melchers 2001, Aven 2003). By formally establishing the maximum tolerance of risk for the public, i.e. the minimum safety requirements, and the maximum for efficient investments into safety, a so-called 'As Low As Reasonably Possible' or ALARP region of relevant strategies for safety management can be established; see Figure 2.

The determination of the maximum risk tolerance and of the maximum for efficient investments differs among the studies. Ditlevsen (2003) employs profiling of the nature of maritime risk, i.e. critical intolerance of high-consequence accidents that possess low occurrence, to establish the minimum acceptable levels of safety. Skjong and Ronold (1998), on the other hand, use a Life Quality Index (Lind 1996) to establish how much should be maximally invested into the prevention of the loss of life. A so-called 'upper bound criterion' of *Implied Cost of Averted Fatality*, or ICAF threshold, is defined on the premise of the economic activity of a life lost. Depending on the area of operations observed, or persons' origin, this value ranges between 300 k€ and about 3 M€. Should the investment into safety be efficient, the CAF, or the *Cost to Avert the Fatality*, defined as the ratio

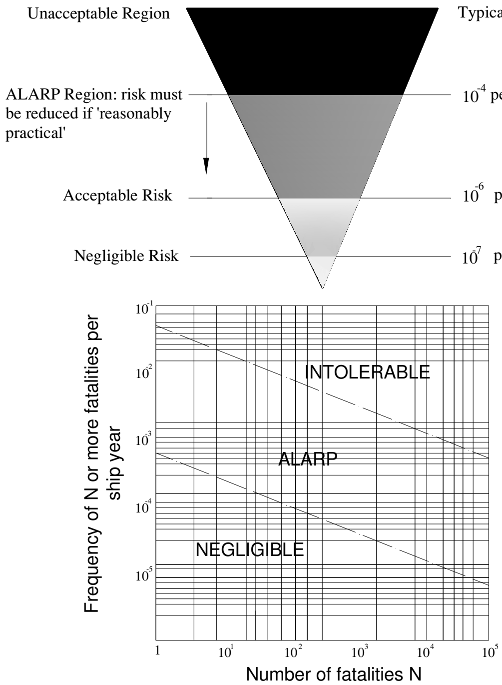

Figure 1. ALARP – 'as low as reasonably practical' probabilities (Melchers 2001) with typical risk acceptance frequency for the number of fatalities (Pedersen 2010)

between the costs of investment in reducing the risk of loss of life and the expected reduction in loss of life, needs to be smaller than the threshold value of ICAF. Ditlevsen and Friis-Hansen (2003), combining the works above, establish a decision criterion for the acceptance of risk by the public to determine the threshold of the maximum amount to be invested into the aversion of environmental loss. The criterion is based on the balance between the benefits of maritime transport to the public and the risks it brings to the public. Following this work, and the work of Skjong and Vanem (2005), the IMO (2008) established the threshold of *Cost to Avert a Tonne of Spillage*, or $CATS_{thr}$, at about 50 k€. CATS[2] itself is established analogously to CAF.

ICAF and $CATS_{thr}$ are very straightforward values for determining the efficiency of the investments being considered, but they lack the capacity to distinguish between low and high risks, as well as between the particular preferences of maritime stakeholders, which are relevant from the point of view of this study. They lack the capacity to determine the optimum amount of investments into safety, i.e. that the design alternative approaching the

[2]Here CATS refers not to the threshold, but to the ratio between the costs of investment and the tons of spillage averted.

threshold would be considered optimal. Furthermore, the values of CAF and CATS should not be used as criteria, i.e. the less the better, as they can produce very misleading figures, where their minima can be found e.g. for very 'cheap' alternatives with a minimum of risk reduction. The opposite, i.e. to maximise CAF and CATS, is irrational. ICAF and $CATS_{thr}$ are also determined in general, so they lack the sensitivity to capture the aspects of a particular ship project. Thus, they can be misleading if applied alone.

As an alternative, Rosqvist and Tuominen (2004) and French *et al.* (2005) consider a multi-attribute decision-making framework. Assuming full compensation for the costs and benefits of safety investments amongst the stakeholders, they establish a more rational framework to determine the optimal amount of investment. No firm or predetermined thresholds are implied, as the selection is based strictly on the preferences of stakeholders. On this basis, and on the IMO's (IMO 2002) recommendation for the fair treatment of stakeholders' preferences, Rosqvist (2003) provides a selection criterion where the optimum of safety investments is found for the design alternative with the fairest distribution of the corresponding risks between the stakeholders.

The validity of the assumption of full compensation amongst stakeholders is reasonable if one considers a very broad domain of stakeholders. Enough stakeholders make up the total economics of maritime transport and are thus part of the fully compensated system. Such a situation then easily correlates with safety as defined in international conventions, industry standards, and practices, e.g. when considering the updating of statutory rules. Within a narrower context, e.g. the structural design of a ship, the validity of the assumption about full compensation amongst stakeholders comes in question. The number of stakeholders involved, i.e. those sensitive to the changes in structural design, is smaller. Obviously, these represent only a part of the total economics, and the assumption of full compensation can no longer be guaranteed. Hence, an alternative approach should be considered.

1.2.2. Game Theory

Vincent and Grantham (1981) show how a design process can be described as a decision-making problem. Designing to satisfy the preferences of multiple stakeholders can then be seen as a group decision-making problem, where each stakeholder is treated as a decision maker.

Differing preferences lead to competitive relationships between stakeholders (Håkansson and Henders 1990). In such relationships, stakeholders are not willing to renounce any of their benefits as they try to maximise them independently (Duetsch 1949, Wilkinson and Young 1994).

Such a decision-making problem is formalised effectively through the theory of mathematical games, or Game Theory (v Neumann and Morgenstern 1944, Meyerson 1991, Keeney and Raiffa 1977). Two types of games can be distinguished. A static game describes a situation in which each stakeholder makes a choice from a fixed set of strategies, and where this set does not depend on the choices made by other stakeholders. A dynamic game, on the other hand, possesses varying sets of strategies, which depend on the choices made. A dynamic game obviously assumes that the choices are made at least twice, and thus it can, in a simplified manner, be understood as a series of static games.

According to the above definition, ship design is a dynamic process. Thus, utilising a dynamic game would be the most appropriate way to map it and thus solve it. However, ship design is also complex, and the elicitation of the available strategies and consequences of the choices made cannot be defined explicitly. Similarly to the game of chess, it cannot be mapped, but it can be tackled.

Maritime stakeholders, through preferences, trade off between the costs and benefits they face with a ship either in production or in operation. In the case of safety, this refers to the cost-effectiveness of any risk control option that is considered. Therefore, a single static game can be derived in such a way that it models the cost-effectiveness of the alternatives and allows the selection of one option that optimally satisfies all stakeholder preferences, as shown in Figure 2.

The 'dynamic' part of the design decision making can be approximated with design optimization; again, see Figure 2. If we are aiming to select the best design alternative, then the alternatives that are considered should be good solutions.

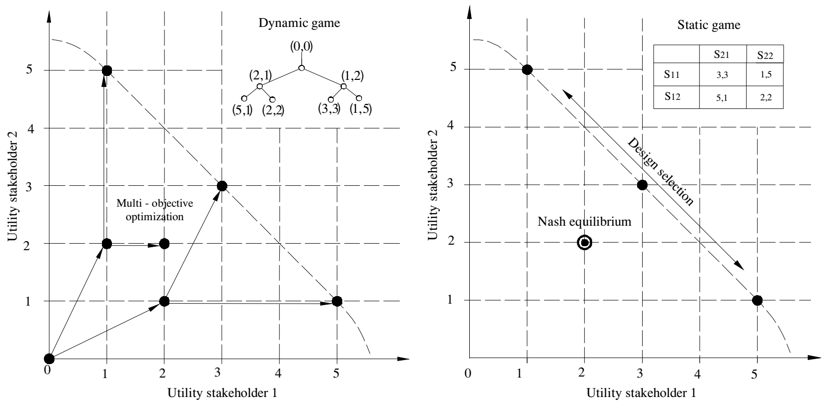

Figure 2. Design decision-making process modelled as a) a dynamic and b) a static mathematical game with the Nash Equilibrium marked.

Speaking in terms of multi-objective optimization, design alternatives considered for selection through a static game should be non-dominated solutions of the optimization problem. The non-dominated solutions, or Pareto optima, possess attributes that are not entirely outranked (dominated) by any other alternative under consideration (Pareto 1896). Extending this to the utilities of stakeholders, the non-dominated design alternatives effectively become compromise solutions between stakeholder preferences. In terms of group decision making, they are collectively stable solutions (Rao *et al.* 1997), i.e. their attributes and utilities cannot all be simultaneously improved by any alterations in order to reach a new feasible design.

Depending on the nature of the game, a static game possesses several well-known solutions, e.g. Min-Max, Bayesian, etc. For the competitive games, the classic solution of Nash (Nash 1951), better known as Nash Equilibrium, is considered often. It is defined as the outcome of the optimal choice of strategies of stakeholders in their response to the optimal choices of others. Such a solution can be defined as 'individually stable' (Rao et al. 1997), referring to the fact that no unilateral decision by any stakeholder will result in higher benefits for that stakeholder than at the Nash Equilibrium.

In this case, the Nash Equilibrium will yield an alternative that optimally distributes the benefits and costs related to the risk reduction amongst the stakeholders. However, Dubey (1986) shows that the Nash Equilibrium of a static competitive game will probably be a non-efficient solution. Saksala (2005) vividly depicted this 'anomaly[3]' for a number of cases in structural design. Such an outcome is then irrational with respect to the considerations of ship design in general, as another alternative can provide more benefits to all stakeholders than the Nash Equilibrium. Special care should thus be taken when considering the application of Nash Equilibrium.

1.2.3. Ship structural optimization for multiple objectives

The optimization of marine structures has been investigated extensively since the 1960s, from the initial papers of Moses (1964), Kavlie et al. (1966), Moe and Lund (1968), and Moses and Onoda (1969), which considered classical methods, via the works of Hughes *et al.* (1980) and Rigo and Fleury (2001), which advanced these methods, to the applications of

[3]It is a disturbing fact that some economic equilibrium, in this case a fair solution, is at the same time irrational, since concurrently another solution exists from which all the stakeholders profit more.

evolutionary optimization methods, such as genetic algorithms. As a result of this effort many interesting features of the problem of the structural optimization of ships have come to light. We are e.g. familiar with the principles of how to make lightweight marine structures – reducing the stiffener spacing to reduce the plating thickness and stiffener size.

However, in principle there has been a significant lack of investigations into optimising ship structures for other objectives. Several studies only focused on the optimization of production costs, e.g. Rigo (2001), Richir *et al.* (2007), or reliability, e.g. Zanic *et al.* (2006). For this reason there is a lack of sufficient experience of ways to improve a ship structure with respect to any other objective but weight. This indicates a gap in the optimization methodology that is capable of optimising ship structures for various objectives other than weight, and also concurrently with weight.

Classical 'text-book' optimization methods, like the method of feasible directions, or conjugated gradients (Rao 2007) are generally capable of solving only small engineering problems with up to 10 or so variables (Hughes *et al.* 1980), which is far from satisfying demands of ship structural optimization. Due to operations with first and second derivatives of objective and constraint functions, optimization in this case typically converges to local optima. And in cases involving large number of variables, there will be a plenty of local optima available and reaching the global optimum becomes more a matter of chance than calculations. Furthermore, the objectives and constraints in ship structural optimization are often not defined explicitly as functions of design variables, e.g. when using FEM. The variables are also often discrete, as for structural scantlings, so derivatives of objectives and constraints cannot be determined, and the classical methods do not apply.

In that respect, the authors mentioned in the beginning of this section, approached amongst others, ship structural optimization by customizing classical optimization methods. This e.g. involved building-in problem information into the optimization method by sequential 'smart' simplification of the optimization problem (Rigo and Fleury 2001). Hughes *et al.* (1980) on the other hand simplified the original global ship optimization problem onto a series of stiffened panel level optimization problems, which are sequentially linearised. These strategies yielded successful problem solutions to many practical problems with hundreds of variables, and were thus implemented in commercial ship structural design software *MAESTRO* and *LBR-5*. However, problems remained with respect to discrete variables, or with optimization of more than a single objective, which continue to be solved indirectly. See more e.g. in Zanic *et al.* (2007) and Caprace *et al.* (2010).

Evolutionary algorithms, due to the different nature of operations have the capacity to solve very large practical problems of ship structural optimization directly. The most notable evolutionary algorithms, with a large base of applications, are the Genetic Algorithms (GA). Using the principles of evolutionary biology – the survival of the fittest, to generate better design alternatives, and genetics – the chromosome string, for the coding of variables, practically any structural optimization problem can be tackled. Unlike the classical methods, they concurrently operate with multiple alternatives, so they are more convenient for multi-objective optimization (Deb 2001), where they can generate a set of optimal alternatives in one calculation run.

Amongst several advantages in comparison to classic methods, GAs demand, however, a much higher number of evaluations. This means that they generate during optimization many more design alternatives. If this were combined with the extremely time-consuming evaluations that are required to e.g. evaluate ship crashworthiness in collision and grounding, optimization with a GA becomes impractical unless the GA can be enhanced.

Two elements come forward for the completion of this challenge. The first is to customise a GA that makes better use of functional information that enhances its search capabilities for the class of problems being considered, while the second is to hasten the evaluation of objectives and constraints.

The enhancement strategies principally address how to utilise more information and force GA to make better decisions about which alternatives to consider and which to skip for the advancement to the optima. This is especially important from the perspective of multi-objective optimization, where there is a desire to attain as many optima as possible. Deb *et al.* (2002) in that sense propose practical techniques, such as crowding and non-dominated sorting strategies in their NSGA-II[4] algorithm to attain a well-spread and well-populated set of optimal alternatives. However, to generate a large Pareto frontier in this way, which occurs if we aim to find the optima between the minimum permissible and maximum attainable safety, a large population is required of about three alternatives per design variable. A large-scale optimization problem with about 100 or more design variables cannot afford such a population size. On the contrary, the minimum possible population size is preferred, of e.g. 50 alternatives. Even though a GA applying the above-mentioned techniques will have a well-spread frontier of alternatives, it will probably miss some of the 'genetic

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[4] Combined with the advanced selection techniques, this GA has become presently one of the most applied optimization algorithms.

material' needed to progress efficiently towards the optima; see e.g. Jelovica and Klanac (2009).

The main working principle of many GAs, including those mentioned above, is that they ignore infeasible solutions, even though these might be close to the boundary of feasibility and possess good values of objectives. The possibility of considering such alternatives and improving a GA's efficiency can be attained with the conversion of constraints into additional objectives, in the approach called 'vectorization'[5]. This approach has been exploited by several authors, such as Osyczka *et al.* (2000) and Deb (2001), and has shown success. However, it has not been studied deeply enough to depict the effects that the conversion of constraints into objectives has on the optimization process, and nor have all the opportunities provided by this approach been explored. It does offer more opportunities to raise the efficiency of GA optimization.

1.2.4. Collisions and grounding of ships

Structural design has already been exploited as a means to manage safety related to accidental loads and breaches of hulls. In the 20th century, nuclear-powered ships faced a clear danger if the reactor were to be physically damaged, e.g. by a ship-to-ship collision. Woisin (1979) described some rearrangements that would result in a higher tolerance of the collision energy of the side structures prior to undergoing breaching. These first investigations served the purpose not only of creating more crashworthy side structure designs, but also capturing the mechanics of ship-to-ship collisions. From that period the work of Minorsky (1959) should be noted, which established the proportional relationship between the capacity to absorb collision energy and the volume of the structure involved in deformation.

McDermott *et al.* (1974) showed that the key element for ship structures to have an extended capacity to absorb energy is to permit the structure to undergo large membrane tension. Following this conclusion, a series of novel designs of both side and bottom structures have been and still are being investigated (Lehmann and Peschmann 2002, Ludolphy and Boon 2000, vd Graaf *et al.* 2004, Naar *et al.* 2002, Klanac *et al.* 2005). Several of these can be seen in Figure 3 below.
What all these studies have in common is that their concept developments focused on the definition of the topology of a novel crashworthy structure.

[5]The term 'vectorization' is based on the conversion of constraints into objectives, which as a consequence leads to their inclusion into the optimization vector, i.e. a vector of objectives to be optimised.

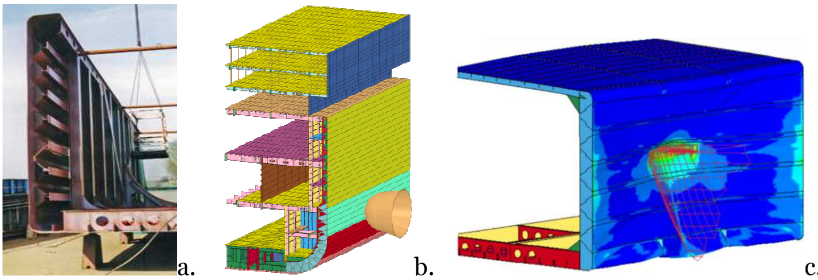

Figure 3. Concepts of crashworthy structures: a) Y-core structure on board an inland waterway gas carrier (Ludolphy and Boon 2000); b) X-core structure on board a RO-PAX (Ehlers et al. 2007), and c) corrugated structure on board an inland waterway gas carrier (Klanac et al. 2005)

Furthermore, no attention was thus given to the redesign of conventional double-sided and double-bottomed structures. Therefore, Ehlers (2010) optimises the scantlings of a conventional tanker side structure in order to improve its crashworthiness. However, he does not consider stakeholder aspects.

1.3. Scope of the work

Based on the indicated research gap in the four observed research areas, i.e. maritime safety, Game Theory, ship structural optimization for multiple objectives, and collisions and grounding of ships, Figure 4 symbolically indicates the scope of this thesis. We can notice that these contributions are principally located at the interfaces of the four observed research areas, and can be classified into: i) design selection; ii) GA optimization; iii) crashworthiness optimization, and iv) safe ship structures.

Game Theory provides a set of concepts to address decision problems involving multiple stakeholders. In cases where full compensation of costs and benefits amongst the stakeholders cannot be guaranteed, an economically stable solution can still be provided using the theory. This solution should be fair, and, unlike the ICAF and $CATS_{thr}$ criteria, it should distinguish between design alternatives with strong safety improvements and those with low safety improvements.

The thesis thus adopts the concept of static competitive games to outline a novel design selection criterion, the Competitive Optimum.

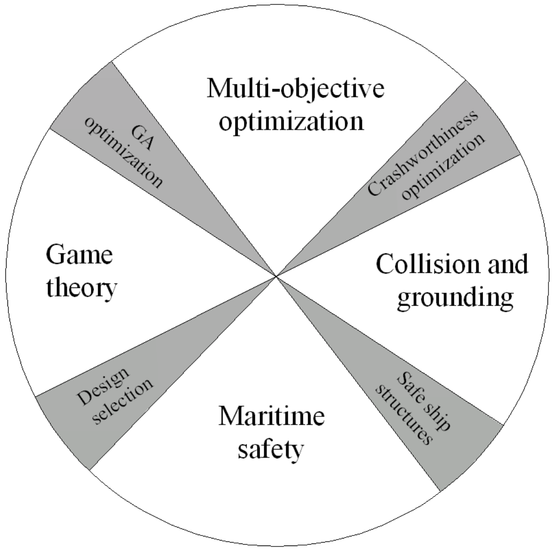

Figure 4. Scope of the work: the basic research fields (in white) and contributions (in grey)

For the Competitive Optimum three fundamental conditions of selection will suffice, i.e. i) non-dominance, ii) efficiency, and iii) maximal stakeholder satisfaction in competitive relationships (MaSSCoR). The latter ensures fairness.

MaSSCoR is based on a Nash Equilibrium solution for static games, which provides the fairest distribution of benefits amongst stakeholders in competitive relationships. But since the Nash Equilibrium of a general static game can be dominated, and hence inefficient, a special static game is constructed assuring that the Nash Equilibrium identifies an alternative that suffices for the first two conditions of selection. To establish this game, we apply multi-objective structural optimization.

Optimization allows the systematic exploration of the design possibilities, thus providing reassurance that the optimal alternatives that are attained are efficient. Since classical optimization methods lack the capacity to solve practical large-scale multi-objective problems, and the current GA optimization also demands a large number of functional evaluations, the thesis proposes a special GA based on vectorization in order to enhance the optimization process. This GA quickens the optimization by converting all design constraints into objectives, providing the necessary advantages in solving problems such as the optimization of ship crashworthiness. A systematic study is conducted on the effects of vectorization, i.e. constraints are not only converted to objectives, but also grouped and partially grouped to provide strategies for approaching large-scale and time-expensive problems. In that sense a novel 'two-step' optimization procedure is proposed.

Two case studies are conducted to illustrate the theoretical contributions that are addressed. The study on the design of a safe double bottom for a Ro-Pax ship with regard to grounding accidents features applications of multi-stakeholder decision making and selection of the double-bottom design that provides the best satisfaction of stakeholders' preferences. Two stakeholders are considered, the yard and the ship owner.

The study on the design of a safe tanker side structure with respect to collision accidents, similarly to the Ro-Pax study, features multi-stakeholder decision-making analysis and design selection using the proposed criterion. The study also features multi-objective optimization of the mid-ship structure with the proposed GA to create the efficient design alternative from which the optimal alternative can finally be selected. The tanker is concurrently optimised for minimum weight and for maximum crashworthiness. Four stakeholders are identified as relevant decision makers, i.e. the yard, the ship owner, the cargo receiver, and the public. Risk analysis is performed, and the risk is defined for each of the efficient alternatives generated and for each of the four stakeholders. The related costs resulting from an increase in crashworthiness are also defined.

1.4. Limitations

The results of this thesis should be observed in the light of the assumptions that are considered, following the desire to focus on the early stages of the design of ship structures.

The Competitive Optimum criterion is based on the concept of Nash Equilibrium, which guarantees fairness towards stakeholder preferences in design selection, and carries the limitation that the list of assumed attributes is not exhaustive. Furthermore, a fundamental element of the Competitive Optimum criterion is the shared perception of the 'Ideal' among the stakeholders. The Competitive Optimum solution will thus hold only as long as all stakeholders perceive all attributes of the 'Ideal' design alternative as a maximal fulfilment of their preferences.

The stakeholder are assumed to be purely competitive, while their preferences are a product of perfect rational thinking with neutral attitude towards risk. This means that a stakeholder will base decisions purely on the expected value of an attribute. This principally holds for institutional and industrial stakeholders, while the public is typically more risk averse, i.e. the adverse expected attribute values are progressively less preferred. In this thesis, however, the public is considered analogically to the institutional stakeholders, since their interests are described in terms of explicit monetary figures which is assumed to exclude emotional aspects that bring front already mentioned risk aversion.

Risk is thus considered equivalent to expected utility[6], and is calculated explicitly following the utility theory (v Neumann and Morgenstern 1944) as a value under uncertainty, i.e. it is a product of consequence costs and the probability that this consequence would occur.

The proposed GA algorithm is based on the conversion of design constraints into objectives, i.e. vectorization. Two types of vectorization are studied in the thesis, absolute and Heaviside. For the optimization of tanker structures, Heaviside vectorization was applied.

The ‘two-step’ optimization procedure is devised on the premise that the process of multi-objective optimization can be split into two phases if the following two types of objectives exist: i) easy to evaluate but difficult to optimise, e.g. the weight of the ship structure, and ii) difficult to evaluate, i.e. time-expensive but easy to optimise, e.g. ship crashworthiness.

Independently of the fact that the proposed GA algorithm with vectorization, through the ‘two-step’ procedure, enhances the optimization of large-scale problems, the evaluation of crashworthiness during the optimization needs to be rapid. Thus, it is evaluated for a single critical collision scenario only. This is a major assumption, which necessitates further validation, and for this reason the practical outcome of the tanker case study is to be treated accordingly.

[6]Utility here is the colloquialism of the ‘expected utility’, and is used throughout the thesis for brevity.

2. The method

There are two most important parts of the proposed design method. The first is the generation of safe design alternatives, and the second is the selection of 'the safe' alternative. The term 'the safest' is deliberately avoided. It strongly impedes other characteristics of such design alternatives, as it is clearly the one with the maximum risk reduction, but not necessarily the one with the best distribution of costs and benefits amongst the stakeholders related to this risk reduction. The method, on the other hand, results in exactly such an alternative.

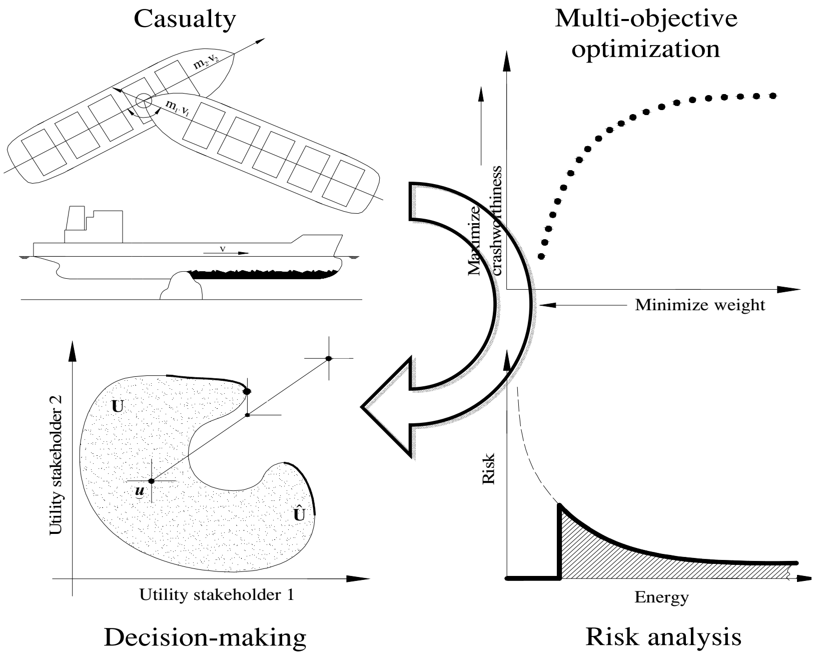

Figure 5. Scheme of the activities in the proposed methodology: leading from an adverse event scenario, e.g. collision or grounding, new optimal design alternatives are generated through multi-objective optimization; they are evaluated for safety (risk analysis) and from the commercial aspect and, finally, an alternative is selected following the multi-stakeholder decision making and the Competitive Optimum criterion.

As mentioned, the method focuses on the structural design of the ship, providing support to designers in determining the best parameters of a structure they design. It is structured on a cycle, shown in Figure 5 above, that is initiated by the analysis of the casualty that is to be mitigated by improving safety. In cases where collisions or grounding are to be mitigated, the ship structure will be optimised for crashworthiness, though without forgetting the commercial aspects of design objectives, e.g. the weight of the ship hull. Following up on this multi-objective optimization, the safe structures that are generated need to be checked for stakeholder preferences, i.e. the costs and benefits of safety investments need to be evaluated exactly. This demands both risk and economic analysis of the impact of the increased crashworthiness. Finally, a safe ship structure can be identified. As with any other method used in ship design, this process can be repeated as many times as is found necessary by the designers.

2.1. Generation of efficient design alternatives

Designing ship structures involves a series of decisions to satisfy owner requirements, class rules, and regulations. The shipyard's production capabilities need to be accounted for as well. Thus, the set of efficient alternatives has to be found using e.g. multi-objective optimization. Finding these alternatives is important if we are to attain general conclusions about some technology, concept, methodology, etc. More precisely, efficient solutions as members of a Pareto frontier indicate the sensitiveness of design objectives to design parameters [P3].

The success of multi-objective optimization in attaining a well-developed Pareto frontier, i.e. having a large number of optimal alternatives well spread between objectives optima, depends on the optimization system that involves an optimization algorithm and computational tools for the evaluation of design objectives/attributes and constraints. If such a system can be properly established, then reaching a Pareto frontier should be a matter of calculation and not of chance.

The design optimization of ship structures is characterised by its design space. It features a multitude of design parameters, often 100 or more, which are also discrete, and a large number of non-linear constraints that create cavities in the design space, making it particularly difficult for an optimiser to search for the objectives minima.

In [P2] and [P3], a special GA is proposed to tackle the optimization of ship structures more efficiently. The principle on which it works mimics the evolution of design. From a set of alternatives, good characteristics are noticed, and these are mixed to generate new alternatives. The algorithm, based on the evolutionary principles of the survival of the fittest, makes decisions from generation to generation about which design information can lead to a Pareto frontier, and thus eventually progresses to the solution. This process is very robust in terms of its ability to find good solutions. On the other hand, it can be time-expensive, sometimes requesting a high number of functional calls. Paper [P2] thus studies the concept of vectorization. Vectorization enhances the use of information on problem objectives and constraints by the algorithm. In this way, constraints are transformed into additional objectives. This adds significant flexibility to the process of optimization. In brief, the algorithm can consider a design as a relevant solution, even though it might be slightly infeasible. Since the boundaries are never absolute this effectively does not directly impede the safety of the system. On the other hand, it serves as a basis for bridging the cavities that plague the design space more easily. This then quickens the search for optima.

In [P3], vectorization is applied as a basis for the new approach to address a specific problem connected to the optimization of ship crashworthiness. Since crashworthiness is calculated with numerical collision simulations, which tend to be extremely time-consuming, the optimization problem is solved in two stages in order to reduce the number of evaluations of crashworthiness. As a result of the conversion of constraints into objectives, vectorization makes possible a directed search during optimization. Therefore, in the first step it is employed to find the minimum structural mass, while ignoring the crashworthiness. This is a more difficult part of optimization, since the minimum mass depends on the constraints, and is often 'hidden' in cavities, which demands a large number of functional evaluations. The second step involves the maximisation of crashworthiness alongside the minimisation of mass. Since the minimum mass is a member of the Pareto frontier, the algorithm, now in its search for the maximum crashworthiness, generates optimal Pareto alternatives along the way. Maximum crashworthiness generally involves a stiffer structure, and thus searching for it is less demanding for the algorithm than minimising mass.

2.2. The Competitive Optimum: selecting the safe ship structure

In [P1][7], a static game is defined, the solution of which is a design alternative that has the optimal amount of safety for the set of alternatives being considered. The game is structured around stakeholders and, more particularly, around their strategies. The strategies model the importance of stakeholders' preferences, or better to say the necessity that these are satisfied. The model is continuous, and in it strategies range between the absolute necessity to select some stakeholder preference or that this preference is irrelevant to the overall decision making. Such a game then allows a wide range of possibilities of modelling different scenarios, for example, that the preferences of all stakeholders are to be taken into account equally or that a certain stakeholder has greater importance than another. This can then represent, for example, the effect of negotiations where one stakeholder overpowers another, or where the preferences of a certain stakeholder are only partially accounted for.

The strategies are established in such a way that any given combination strictly yields a Pareto optimal design alternative, either feasible or infeasible, and that every Pareto optimal alternative under consideration for selection is the result of at least one combination of chosen strategies, as proven in [P1] and [P4]. In this case the Nash Equilibrium will, by default, be Pareto optimal, and we can conclude that the Nash Equilibrium, indicating the optimal amount of safety, will be both an individually and a collectively stable solution. The Nash Equilibrium of this game thus indicates the best possible compromise solution amongst the stakeholders for any design scenario that is considered.

The game, however, consists of both feasible and infeasible alternatives. Of course, only a feasible choice is acceptable, and since the Nash Equilibrium, by definition, cannot differentiate between the two, an alternative solution is proposed. It is named the Competitive Optimum, and it is an alternative displaced from the Nash Equilibrium, should it be infeasible, such that it is no worse than the Nash Equilibrium for any stakeholder, and for at least one, it is better. If the Nash Equilibrium is feasible, then it is also the Competitive Optimum. As such, the Competitive Optimum is adopted as the final criterion for selection in the design of safe ship structures.

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[7] In [P4] the definition of this game is extended from two to three or more stakeholders.

3. Discussion

The Competitive Optimum design maximally concurrently satisfies the preferences of stakeholders, and thus minimizes the negative effect of unbalanced distributions of risks. As mentioned earlier, risk distribution is unbalanced as a result of the scheme of liabilities determined according to the maritime conventions, namely the CLC 1992 and the IOPC 1992 fund. These determine the maximum liability of either the ship owner or the cargo owner in a maritime accident. The remaining costs, which are not covered by these liability limitations, are effectively taken on by the public, e.g. through the actions of the government, such as supportive measures to the affected parts of the public for their losses.

Besides the value that might be lost, it is obvious that any accident involving pollution will have both an immediate and a long-lasting impact on the stakeholders. This is especially valid for the public, as the pollution would change the local way of life, business, etc. On the other hand, the benefits of tolerating the same risk are explicit and direct for the ship and cargo owners only, while they are implicit for the public. Furthermore, some parts of the public, in particular those belonging to the countries excluded from the supply chain, do not partake in its benefits at all.

The results of the case study in Paper 4 indicate a severe imbalance in risk distribution amongst stakeholders, confirming and justifying the fear that the public expresses towards the transportation of pollutants. Figure 6 interprets this statement graphically, indicating the principal environmental risk distribution.

As shown in Figure 6, an additional imbalance amongst stakeholders is exerted by the distribution of influence on risk management. The public has a very low influence on risk management, principally setting only the minimum requirements through the actions of its representatives in the IMO or their Flag States. The biggest impact and responsibility is on the

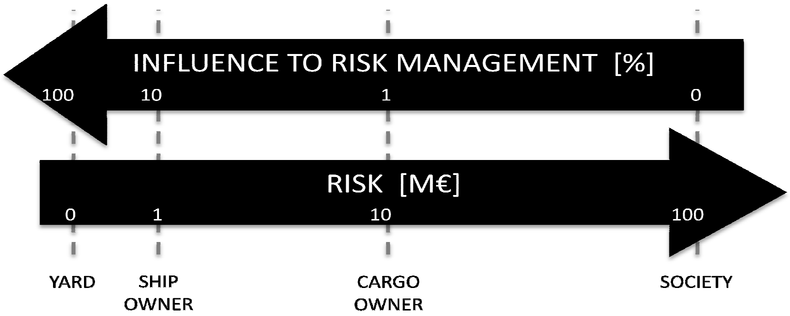

Figure 6. Principal distribution of the environmental risk among stakeholders for a small to medium tanker size (40 to 75 thousand tons DWT), and the influence of these stakeholders on risk management.

yard designing and building the structure, while the impacts of ship and cargo owners on risk management are inversely proportional to their share of the risk. Such a situation is not a coincidence, nor is it unjustifiable. Ultimately, yards and owners finance and invest in the building of the marine structure, while the public obviously does not. Furthermore, these stakeholders face competition and potentially disturbing market changes. Mostly for these reasons, and because of the low risk they face, yards and owners favour a conservative approach in design and do not typically pursue safety improvements beyond the set minimum requirements. Thus it becomes critical to address the preferences of the public during every particular design exercise if one is to justify a safer design on economic grounds. Speaking technically, the key element is to determine the risks facing stakeholders for every design alternative considered.

The advances in decision making and design optimization described here help us to realise the general implications of the proposed methodology for the future design of ship structures. Observing the results of practical case studies, presented in [P3] and [P4], it can be concluded that the design of safe ship structures is reasonable only if it is observed holistically, i.e. if all the relevant stakeholders are considered during design selection. Otherwise, if only those stakeholders who manage risks directly are considered, it is reasonable to maintain the actual design strategy for the minimum requirements.

The results of the case studies clearly indicate that the environmental risk is directly related to the crashworthiness of the ship hull, where an increase in crashworthiness reduces the cargo capacity as a result of the increased hull weight, leading eventually to reduced transport profitability. This loss ultimately needs to be compensated for if we are to design for an economically stable solution. This compensation is provided by the public, as it benefits significantly from the improved crashworthiness as a result of its much higher risk exposure than the other stakeholders.

The results also indicate the way the safe ship structure should be designed, or improved from the present-day state of the art. For example, they show that the most efficient way of increasing safety against grounding in the case of a Ro-Pax vessel is to stiffen the bottom shell structure. A similar but more profound aspect is indicated for tanker safety against collisions, and that is to stiffen only a critical area of the outer shell, below the waterline and above the bilge, while leaving the remainder of the structure as flexible as possible.

4. Conclusion

This thesis proposed a method for the design of safe ship structures. With a focus on accident safety, the method is based on a newly established multi-objective optimization approach for large-scale and time-expensive problems and on a new design selection criterion considering multiple stakeholder preferences in a realistic economic environment.

The new approach to multi-objective optimization is based on a 'two-step' procedure using a special GA with vectorised problem formulation. The design selection approach is based on a new criterion, the Competitive Optimum, which combines non-dominance, efficiency, and fairness, established through the condition of maximal stakeholder satisfaction in the competitive relationships.

Each of these contributions is illustrated with practical studies, i.e. the design selection of a safe Ro-Pax double bottom structure for grounding, and the optimization and design selection of a safe tanker structure for collisions. The case studies resulted in the following set of general design implications.

i) By increasing ship crashworthiness, a significant risk reduction can be attained.

ii) Raising safety is economically justified if the benefits to the public are considered alongside those to industry.

iii) The crashworthiness of ships can be effectively controlled with conventional double-bottom and double-sided structures.

The attainment of such results obviously calls for further research. An obvious step to follow this thesis would be to perform a certain number of new applications of the methodology, to different ship types, and, more profoundly, to different types of adverse events. A holistic overview of the structural safety of ships, with a spectrum of potential adverse events being considered, can also be envisioned. With the application of greater computing power, such as cluster or cloud computing, a more precise assessment of the crashworthiness of ships could be performed, involving e.g. multiple collision simulations.

Besides these design activities, efforts should be made to test different axiomatic definitions of the Competitive Optimum solution, where the distribution of risks and benefits of their mitigation is no longer as fair as possible, but different, e.g. dictatorial with respect to a certain stakeholder, or a consequence of a contract.

In this respect a very handy application of the method could be for a reverse engineering type of study, where relevant maritime accidents could be investigated with respect to the satisfaction of stakeholder preferences, and the cause and effect of the accidents linked with an established design arrangement. This type of research activity should also focus on interviewing stakeholders, as it will produce a more realistic set of preferences, with significant implications of subjectivism and perceived valuation. A direct assessment of stakeholder preferences would ensure a higher level of validity of practical results. A combination of direct stakeholder preference assessments and applications to several practical case studies could also lead to the establishment of more general conclusions and yield a basis for new efficient and economically stable safe structural concepts.

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In project Druzba Adria (2002-2005), Russian crude oil would had been exported by tankers from the North Adriatic, where it would arrive by a pipeline. The project infamously failed as a result of the intensive public outcry for the protection of the environment. Counter-initiatives were strictly conducted in Croatia, and nothing similar occurred in any other country with a shoreline touching the Adriatic. On the other hand, no specific measures were taken by the government or industrial stakeholders to implement safer operations beyond the minimum requirements of industry standards and international conventions. The irony of such an outcome is in the fact that during the time of the planning of the project, and still today, a very intensive import traffic of Arabian oil was conducted at the harbour of Trieste, Italy, located also in the North Adriatic. And no protests were heard. We can wonder whether the outcome would have been different if the Croatian government and industry had had the capacity to implement ships with improved crashworthiness.

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